

ORIGINAL ARTICLE

Why are living things sensitive to weak magnetic fields?

Abraham R. Liboff

Department of Physics, Oakland University, Rochester Hills, MI, USA

Abstract

There is evidence for robust interactions of weak ELF magnetic fields with biological systems. Quite apart from the difficulties attending a proper physical basis for such interactions, an equally daunting question asks why these should even occur, given the apparent lack of comparable signals in the long-term electromagnetic environment. We suggest that the biological basis is likely to be found in the weak (~50 nT) daily swing in the geomagnetic field that results from the solar tidal force on free electrons in the upper atmosphere, a remarkably constant effect exactly in phase with the solar diurnal change. Because this magnetic change is locked into the solar-derived everyday diurnal response in living things, one can argue that it acts as a surrogate for the solar variation, and therefore plays a role in chronobiological processes. This implies that weak magnetic field interactions may have a chronodisruptive basis, homologous to the more familiar effects on the biological clock arising from sleep deprivation, phase-shift employment and light at night. It is conceivable that the widespread sensitivity of biological systems to weak ELF magnetic fields is vestigially derived from this diurnal geomagnetic effect.

Keywords

Biological clock, chronodisruption, cryptochrome, magnetic diurnal change, melatonin, weak-field interactions

History

Received 11 April 2013
Revised 25 April 2013
Accepted 6 May 2013
Published online 17 July 2013

Introduction

Dozens of well-documented experimental reports over the past 40 years clearly indicate that living things are sensitive to weakly intense, extremely low-frequency magnetic fields. This response is puzzling, not only because the electromagnetic intensities involved are well below levels that might conceivably result in meaningful Faraday induction or Joule heating, but also because of the extensive variety of biological models that are affected. This variety is illustrated in Table 1, which lists chronologically a number of key reports where these effects have been observed. For most of the cases in this list, replications have also published, notably including those on lymphocytes (Belyaev et al., 2001), amino acid conductivity (Alberto et al., 2008; Pazur, 2004), planaria regeneration (Novikov et al., 2008) and rat behavior (Zhadin et al., 1999). Moreover, the article on plant growth (Galland and Pazur, 2005) includes an extensive review of other relevant studies.

These observations are usually considered different from those involving the use of the geomagnetic field (GMF) in navigation as in birds, honeybees and turtles. This is partly because the puzzle surrounding the mechanism(s) at the heart of the navigation question is almost always framed in terms of the magnetostatic field as opposed to time-varying fields. Nevertheless, there is some similarity between these two research areas. The maximum sensitivities involved in the magnetic navigation (Semm and Beason, 1990) and ELF reports (Zhadin et al., 1998) are about the same, namely in

the 10–100 nT range. Furthermore, this distinction may be blurred for another reason, depending on the actual mechanism being used. If a bird “recognizes” a certain field strength that is pre-loaded into its memory at birth or through learning, then indeed a mechanism involving the static field is critical. However, it is also conceivable that the bird makes use of *changes* in the local field as part of its navigational regimen; sensing changes are important if it uses an inclination compass (Wiltschko and Wiltschko, 1972). In this case, the question of animal navigation should also be included along with the other examples listed in Table 1. On the other hand, this argument does not hold for the well-documented data showing that magnetotactic bacteria (Frankel et al., 1979) are sensitive to the GMF. There is no question here that the only mechanism at work involves the static GMF.

Theoretical explanations for the “unreasonable” effects listed in Table 1 have included arguments based on ion cyclotron resonance (Liboff, 1985), parametric resonance (Blanchard and Blackman, 1994; Lednev, 1991), increased ionic drift velocity (Vincze et al., 2008) and quantum electrodynamic formation of ion-free water domains (Del Giudice et al., 2002). Apart from the lack of understanding at the molecular level, one can also ask (in contrast to the navigation problem) whether such interactions make biological sense. This question is difficult to answer, considering the apparent lack of widespread ELF magnetic fields in the natural environment over evolutionary times. The 50/60 Hz power burden on living things has only been in existence for little more than a hundred years, too short a time to have possibly resulted in appreciable evolutionary adaptation. Instead, this remarkably wide variety of ELF biological

Address correspondence to Abraham R. Liboff, 16766 Knightsbridge Lane, Delray Beach, FL 33484, USA. E-mail: arliboff@aol.com

effects, all of which are equally unexplainable, probably should be regarded in a broader context, that is, as different examples of some previously unsuspected single biological effect. In the following, we develop this idea, suggesting that weak-field ELF magnetic interactions are the consequence of evolutionary adaptation to the eons-long diurnal change in the geomagnetic field.

The GMF diurnal effect

Careful measurements of GMF intensity indicate a small daily oscillation of approximately 50 nT (Hitchman et al., 1998). This effect is due to the tidal effect of the sun’s gravity on

the earth’s atmosphere, specifically on free electrons in the ionosphere. The current that results from this charge motion typically generates daily magnetic changes such as those shown in Figures 1 and 2.

Figure 1 shows that this diurnal variation affects the declination angle by a few tenths of one degree, whereas Figure 2 shows the change in the horizontal component of geomagnetic intensity, on the order of tens of nT. These examples are typical of what is observed on “quiet” days, when there is no solar activity. Although changes in the GMF due to solar storms can be much greater, sometimes reaching into the 1000s of nT, this diurnal variation is always present, albeit often masked by the much larger solar storm effects.

It is important to note that the changes in magnetic declination shown in Figure 1 and GMF horizontal component happen only during daylight hours. One reasonable model to explain these data hypothesizes that ultraviolet radiation from the sun ionizes atoms in the upper atmosphere, at a height of approximately 100 km, thereby providing a source of free electrons that are moved *en masse* because of tidal effects due to the sun’s gravity (Chapman, 1918). The resulting current generates the change in magnetic field that is observed diurnally. In support of this tidal explanation, one should also expect a much smaller effect, attributable to lunar gravity. Indeed, such a lunar tidal effect is also observed as a small correction to the larger effect. Furthermore, the overall effect varies in a predictable manner with latitude. The picture that emerges is a daily 25–50 nT swing in the GMF that is tied to the level of sunlight received at the top of the atmosphere, thereby providing an alternate source of precise and constant information as to the onset of sunlight.

In addition to this daily swing in GMF, there are also effects due to solar storms. The far larger effects stemming from solar activity can be regarded as perturbations to this diurnal change. In other words, apart from the sporadic effects related to solar storms, there is a baseline 25–50 nT variation

Table 1. Key reports illustrating weak-field, ELF biomagnetic interactions.

Biological model	References
Rat behavior	Thomas et al. (1986)
Diatom motility	Smith et al. (1987)
Protein synthesis in salivary gland cells	Goodman and Henderson (1988)
Mitogenesis in lymphocytes	Cossarizza et al. (1989)
Production of glycosaminoglycans in cartilage	Smith et al. (1991)
Neuroblastoma cell metabolism	Smith et al. (1992)
Expression of insulin growth factor II	Fitzsimmons et al. (1995)
Regeneration of planarians	Jenrow et al. (1995)
Analgesia in snails	Prato et al. (1996)
Rat EEG	Vorobyov et al. (1998)
Amino acid conductivity in aqueous solutions	Zhadin et al. (1998)
Protein hydrolysis	Novikov and Fesenko (2001)
Growth rate in plants	Galland and Pazur (2005)
Stem cell differentiation	Gaetani et al. (2009)

Note the wide variety of biological models. Signals used to elicit these responses include extremely low frequency (ELF), combined magnetic field (ICR) and pulsed electromagnetic field (PEMF).

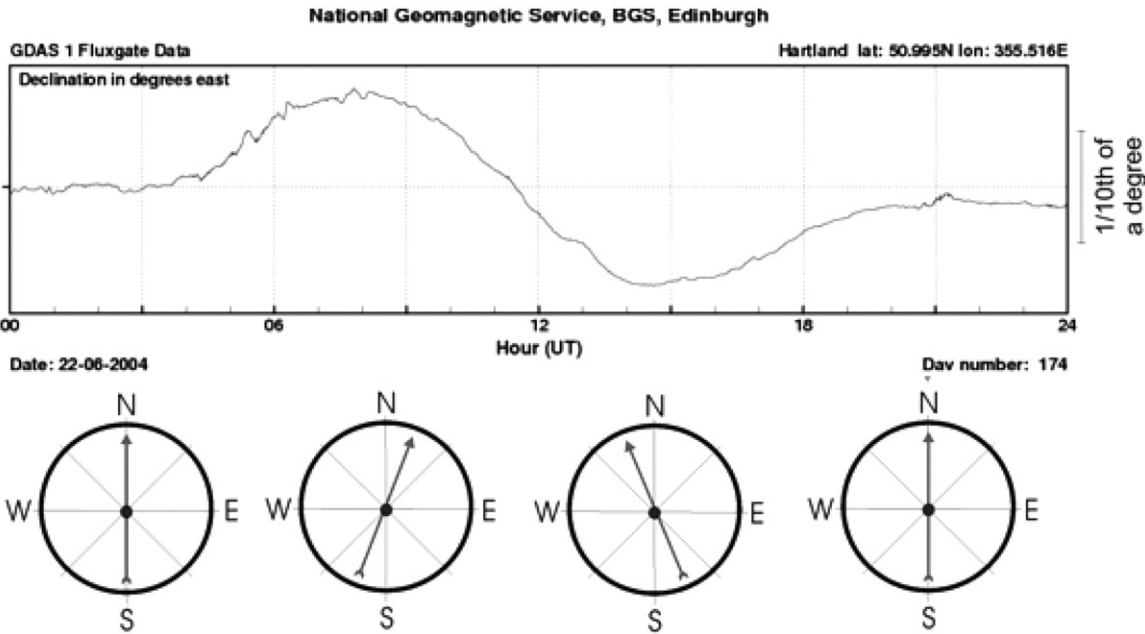


Figure 1. The magnetic declination angle measured during a single day in 2004, with (exaggerated) compass directions shown below. Note that the variation is not exactly synchronized to the 24-h period, but begins and ends within the smaller period corresponding to daylight hours (Source: Brit Geol Survey, <http://www.geomag.bgs.ac.uk>).

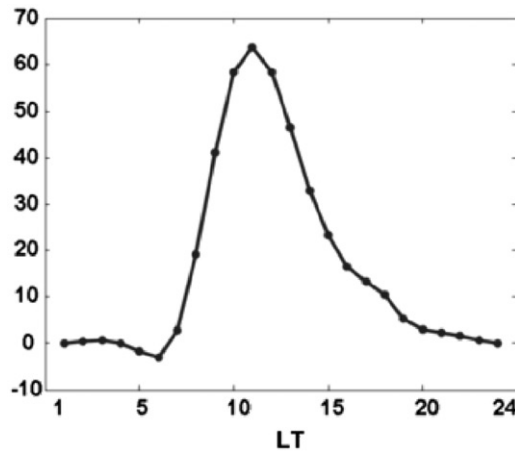


Figure 2. Change in the horizontal component of the GMF measured in nT plotted against local time in hours (LT) clearly showing the 24-h variation. Change is the most prominent during daytime hours. (en.wikipedia.org/wiki/equatorial-electrojet).

that has been present since the earliest formation of the atmosphere, billions of years ago, even before the first appearance of life on earth. Only two conditions are required for this effect to occur: ultraviolet radiation from the sun and the consequent tidal-induced flow of electrons.

The fact that this small but significant daily variation in GMF is firmly locked in phase with the hours of sunlight strongly suggests that this effect may somehow act as a surrogate for biological clock activities. We further note that there is well-established evidence for biological sensitivity at levels in the same 25–50 nT range, specifically with regard to bird navigation (Beason, 2005; Semm and Beason, 1990) as well as the conductivity of amino acids in aqueous solutions (Alberto et al., 2008; Zhadin et al., 1998).

Weak ELF magnetic fields are chronodisruptive

There are good arguments linking magnetic fields to the biological clock (Close, 2012). The present understanding of the clock mechanism in mammals is that awareness of light vs. dark is found in the interplay between the eye and the suprachiasmatic nucleus (SCN), a concentrated group of cells in the brain. The SCN receives its primary signals from the retina but also interacts with the pineal gland. Its function is to synchronize clock cells by sending endocrine signals to various tissues peripheral to the brain – the heart, lungs, gastrointestinal tract, kidneys and connective tissues.

The role of the retina is to recognize the onset of light in order to maintain the phase of the clock. This is accomplished by the presence of at least two different types of photoreceptive proteins in the retinal ganglion cell layer (Brainard et al., 2001; Sancar, 2000). Although there is no evidence to indicate that the SCN is itself responsive to magnetic fields, it has been established (Olcese et al., 1985) that the retina does respond to weak magnetic fields, affecting the melanopsin receptors, precursors to melatonin.

The pineal gland produces melatonin, a potent antioxidant, but this production only occurs in darkness when the retina is not receiving light. Chronodisruptive problems related to biological clock function (Erren et al., 2008; Stevens, 2006)

are in part a consequence of reduced melatonin production, which in turn reduces the repair of cellular components that may have been damaged during daylight hours.

Not only light but also ELF magnetic fields are known to block the production of night-time melatonin (Reiter, 1993; Selmaoui and Touitou, 1995). The fact that both light and magnetic fields affect the biological clock, both by means of excitations in the retina, may imply a common evolutionary history, whereby both modalities were together folded into living things in complementary ways. This speculation is strengthened by realizing that there is yet another component of the biological clock that is responsive to magnetic fields that is also found in the retina. The cryptochromes (Cashmore, 2003) are photoreceptors found in plants and animals that absorb light and transmit electrical signals to the clock. These retinal photoreceptors are distinct from the melanopsins also found in the eye. Furthermore, cryptochrome lends itself to magnetochemical sensitivity because it forms radical pairs upon photoexcitation (Liedvogel and Mouritsen, 2010; Ritz et al., 2000).

Because of the magnetic sensitivity enjoyed by these two retinal photoreceptors, both key components of the biological clock, it is clear that responses to variations in the local magnetic field are incorporated into a clock function. It follows that out-of-phase magnetic changes may be chronodisruptive, similar to the way that light reception not in phase with the existing biological clock can cause problems such as those stemming from jet lag, sleep deprivation and phase-shift employment (Henshaw and Reiter, 2005).

In pursuing this question, it is also important to distinguish the effects due to short-term changes in the magnetic field from those reflecting different levels of baseline magnetic field. One can draw upon the analogy to the effect of altered light burdens on clock function. Individuals may react negatively to a sudden large change in longitudinal location as happens in jet lag but this problem is self-repaired after a few days by an adjustment of the biological clock to the new ambient conditions. In the magnetic case, the system will again respond to the short-term changes as it does during solar storms, but will readjust following long-term exposure to a different background field.

This is clearly a question of some complexity: consider that even the way light that affects the biological clock is not yet completely understood. We assume for the sake of simplicity that the magnetically responsive aspect of the biological clock is affected by ambient magnetic fields in only two ways, either by adaptation to a long-standing baseline static field or by a sudden shift in this baseline. Individuals can accommodate to the fields in different regions of the globe, but will respond negatively to sudden local changes caused by solar storms. Above all, we note that superposed on this proposed system is the ever-present diurnal 25–50 nT change.

Solar storms are similarly chronodisruptive

Thus, it is reasonable to suggest that magnetic chronodisruption effects probably explain the widespread reports linking medical problems to solar-related geomagnetic perturbations (Close, 2012). Although the data in such reports are obtained

Table 2. Myocardial infarctions in Yekaterinburg, comparing solar active or solar quiet periods.

Year	Morbidity			Mortality		
	Active	Quiet	% Increase	Active	Quiet	% Increase
1961	78.8	70.4	8.4	24.5	18.8	5.7
1962	73.5	65.3	8.2	35.0	25.7	9.3
1963	77.6	73.2	4.2	24.9	20.6	4.3
1964	62.0	57.0	5.0	36.4	21.7	14.7
1965	79.1	75.0	4.1	27.9	25.3	2.6
1966	90.8	75.4	15.4	59.5	40.9	18.6
Mean %			7.5			9.2

Thus, in 1964, heart attacks occurred 57% of the time on quiet days but 62% on active days, with a 5% greater incidence of heart attacks that year due to solar activity. The year 1966 was marked by a large increase in solar storms, consistent with the sun’s 11-year cycle (Novikova and Ryvkin, 1977).

using the limited techniques of correlation analysis, one cannot deny their long-term consistency. These correlations have been reported for at least 75 years starting with a multi-year comparison of death records to solar activity (Dull and Dull, 1935). One finds persistent indications for increased psychiatric hospitalization (Friedman et al., 1963), suicide rate (Berk et al., 2006) and cardiac infarcts (Mendoza and Diaz-Sandoval, 2000) that are tied to solar storms.

The most extensive studies have focused on heart disease, where investigators in a number of different cities find an increase of approximately 10% in the incidence of heart attacks on days when solar-related geomagnetic activity occurs. One such example is shown in Table 2, which summarizes medical data taken over the course of 6 years in one Russian city (Novikova and Ryvkin, 1977).

Discussion

We have explored a new approach to understanding the question of weak-field biointeractions. The daily variation of the GMF, and especially the fact that it is in phase with the receipt of sunlight, suggests that it serves as a surrogate to help organisms maintain their biological clock. This argument is strengthened by the recently discovered sensitivity of the biological clock to magnetic fields, as well as by increasing evidence that geomagnetic changes due to solar storm activity are chronodisruptive.

Both primitive and advanced organisms are unusually responsive to weak magnetic fields, both phenomena with limited understanding of the underlying physical mechanisms. In advanced systems, such as the bird, it is likely that the magnetochemical properties of cryptochrome result in neural signals to the central nervous system that allow local magnetic information to assist in navigation. But in simpler systems, such as those studied in cell culture, there is no comparable sensory response. One can imagine that for both systems, the simple and the complex, related biophysical processes are at work. In this scenario, the appearance of magnetically sensitive photoreceptors in the eye did not appear fully developed *de novo*, but were preceded by the systems with relatively simple sensory mechanisms, aspects of which have been carried through to the present.

The fact that there are two distinct magnetically responsive photoreceptors in the eye is remarkable. Nature must attach a considerable importance to the magnetic response, an observation that is reinforced when examining the variety of systems affected in Table 1, to say nothing about the fact that all organisms appear to be sensitive in one way or another to the GMF.

Recognition that the tidal variations in geomagnetic field also include a second-order lunar component may shed light on an older biological puzzle. Some 50 years ago Brown reported that many organisms, ranging from fiddler crabs (Webb and Brown, 1965) to bean seeds (Brown and Chow, 1973), exhibited cycles specifically tuned to the lunar cycle. This work hints at a possible solution to this question, one that is based on weak-field magnetic interactions.

In summary, we speculate that the widely observed weak-field biomagnetic responses typified in Table 1 stem from early evolutionary recognition of the diurnal change in the GMF as a precise zeitgeber; indeed one that outperforms the sun itself, in that it happens independently of cloudy skies. The need for a functioning biological clock would have necessitated early magnetic detection mechanisms that would, in time, not only have evolved differently for different genera but would have provided opportunities for various advantageous applications. Note that this concept does not provide an answer to the exact nature of the mechanism, other that it must have first appeared in the earliest organisms. If one accepts this speculation, then one can also argue that all the ELF biointeractions, including those that are listed in Table 1 as well as those involving navigational application, have their remote origins in the earliest adaptations of living things to the diurnal change in the GMF.

Declaration of interest

The author reports no conflicts of interest. The author alone is responsible for the content and writing of this article.

References

Alberto, D., Busso, L., Garfagnini, R., et al. (2008). Effects of extremely low-frequency magnetic fields on L-glutamic acid aqueous solutions at 20, 40, and 60 micro T magnetic fields. *Electrom. Biol. Med.* 27: 241–253.

Beason, R. C. (2005). Mechanisms of magnetic orientations in birds. *Integr. Comp. Biol.* 45:565–573.

Belyaev, I. Y., Alipov, E. D. (2001). Frequency-dependent effects of ELF on chromatin conformation in *Escherichia coli* cells and human lymphocytes. *Biophys. Biochim. Acta* 1526:269–276.

Berk, M., Dodd, S., Henry, M. (2006). Do ambient electromagnetic fields affect behavior? A demonstration of the relationship between geomagnetic storm activity and suicide. *Bioelectromagnetics* 27: 151–155.

Blanchard, J. P., Blackman, C. F. (1994). Clarification and application of an ion parametric resonance model for magnetic field interactions with biological systems. *Bioelectromagnetics* 15:217–238.

Brainard, G. C., Hanifin, J. P., Greeson, J. M., et al. (2001). Action spectrum for melatonin production in humans: evidence for a novel circadian photoreceptor. *J. Neurosci.* 21:6405–6412.

Brown, F. A., Chow, C. S. (1973). Lunar correlated variations in water uptake by bean seeds. *Biol. Bull.* 145:265–278.

Cashmore, A. R. (2003). Cryptochromes: enabling plants and to determine circadian time. *Cell* 114:537–543.

Chapman, S. (1918). Diurnal changes of the earth’s magnetism. *The Observatory* 41:52–60.

Electromagn Biol Med Downloaded from informahealthcare.com by University of Laval on 12/29/14
For personal use only.

- Close, J. (2012). Are stress responses to geomagnetic storms mediated by the cryptochrome compass system? *Proc. Biol. Sci.* 279:2081–2090.
- Cosarizza, A., Monti, D., Bersani, F., et al. (1989). Extremely low frequency pulsed electromagnetic fields increase cell proliferation in lymphocytes from young and aged subjects. *Biochem. Biophys. Res. Commun.* 160:692–698.
- Del Giudice, E., Fleischmann, H., Preparata, G., Talpo, G. (2002). On the “unreasonable” effects of ELF magnetic fields upon a system of ions. *Bioelectromagnetics* 23:522–530.
- Dull, T., Dull, B. (1935). Correlations between disturbances in terrestrial magnetism and frequency of deaths (in German). *Deutsch Med Wochenschr* 61:95–97.
- Erren, T. C., Pape, H. G., Reiter, R. J., Piekarski, C. (2008). Chronodisruption and cancer. *Naturwissenschaften* 95:367–382.
- Fitzsimmons, R. J., Ryaby, J. T., Mohan, S., et al. (1995). Combined magnetic fields increase insulin-like growth factor II in TE-85 human osteosarcoma cell cultures. *Endocrinology* 136:3100–3106.
- Frankel, R. B., Blakemore R. P., Wolfe, R. S. (1979). Magnetite in freshwater magnetotactic bacteria. *Science* 203:1355–1356.
- Friedman, H., Becker, R. O., Bachman, C. H. (1963). Geomagnetic parameters and psychiatric hospital admissions. *Nature* 200:626–628.
- Gaetani, R., Ledda, M., Barile, L., et al. (2009). Differentiation of human adult cardiac stem cells expose to extremely low-frequency electromagnetic fields. *Cardiovasc. Res.* 82:411–420.
- Galland, P., Pazur, A. (2005). Magnetoreception in plants. *J. Plant Res.* 118:371–389.
- Goodman, R., Henderson, A. S. (1988). Exposure of salivary gland cells to low-frequency electromagnetic fields alters polypeptide synthesis. *Proc. Natl. Acad. Sci. USA* 85:3928–3932.
- Henshaw D. L., Reiter, R. J. (2005). Do magnetic fields cause increased risk of childhood leukaemia via melatonin disruption? *Bioelectromagnetics* 7:86–97.
- Hitchman, A. P., Lilley, F. E. M., Campbell, W. H. (1998). The quiet daily variation in the total magnetic field: global curves. *Geophys. Res. Lett.* 25:2007–2010.
- Jenrow, K. A., Smith C., Liboff, A. R. (1995). Weak ELF fields and regeneration in the planarian *Dugesia tigrina*. *Bioelectromagnetics* 16: 106–112.
- Lednev, V. V. (1991). Possible mechanism for the influence of weak magnetic fields on biological systems. *Bioelectromagnetics* 12:71–75.
- Liboff, A. R. (1985). Geomagnetic cyclotron resonance in living cells. *J. Biol. Phys.* 13:99–102.
- Liedvogel, M., Mouritsen, H. (2010). Cryptochromes – a potential magnetoreceptor. *J. R. Soc. Interface* 7:S147–S162.
- Mendoza, B., Diaz-Sandoval, R. (2000). Relationships between solar activity and myocardial infarction in Mexico City. *Geofis. Int.* 39: 53–56.
- Novikov, V. V., Fesenko, E. E. (2001). Hydrolysis of some peptides and proteins in a weak combined (constant and low-frequency variable) magnetic field. *Biophysics* 46:233–238.
- Novikova, K. F., Ryvkin, B. A. (1977). Solar activity and cardiovascular disease. In: Gneyshev, M. N., Ol, A. J. eds., *Effect of Solar Activity on the Earth's Surface and Biosphere. Acad Sci USSR. (Translated from the Russian)*. Jerusalem: Israel Program Scientific Translations. pp. 184–200.
- Novikov, V. V., Sheiman, I. M., Fesenko, E. E. (2008). Effect of weak static and low-frequency alternating magnetic fields on the fission and regeneration of the planarian *dugesia* (*Girardia*) *tigrina*. *Bioelectromagnetics* 29:387–393.
- Olcese, J., Reuss, S., Vollrath, L. (1985). Evidence for the involvement of the visual system in modulating magnetic field effects on pineal melatonin synthesis in the rat. *Brain Res.* 333:382–384.
- Pazur, A. (2004). Characterisation of weak magnetic field effects in an aqueous glutamic acid solution by nonlinear dielectric spectroscopy and voltammetry. Available from: <http://www.biomagres.com/content/2/1/8> (accessed 8 Jun 2013).
- Prato, F. S., Kavaliers, M., Carson, J. J. (1996). Behavioral evidence that magnetic field effects in the land snail *Cepaea nemoralis* might not depend on magnetite or induced electric currents. *Bioelectromagnetics* 17:123–130.
- Reiter, R. J. (1993). Static and extremely low frequency electromagnetic field exposures: reported effects on the circadian production of melatonin. *J. Cell Biochem.* 51:393–403.
- Ritz, T., Adem, S., Schulten, K. (2000). A model for photoreceptor-based magnetoreception in birds. *Biophys. J.* 78:707–718.
- Sancar, A. (2000). Cryptochrome: the second photoactive pigment in the eye and its role in circadian photoreception. *Ann. Rev. Biochem.* 69:31–67.
- Selmaoui, B., Touitou, Y. (1995). Sinusoidal 50-Hz magnetic fields depress rat pineal NAT activity and serum melatonin. Role of duration and intensity of exposure. *Life Sci.* 57:1351–1358.
- Semm, P., Beason, R. C. (1990). Responses to small magnetic variations by the trigeminal system of the bobolink. *Brain Res. Bull.* 25:735–740.
- Smith, S. D., Liboff A. R., McLeod, B. R. (1991). Effects of resonant magnetic fields on chick femoral development in vitro. *Electrom. Biol. Med.* 10:81–89.
- Smith, S. D., Liboff, A. R., McLeod, B. R., Barr, E. J. (1992). Effects of ion resonance tuned magnetic fields on N-18 neuroblastoma cells. In: Allen, M. J., Cleary, S. F., Sowers, A. E., Shillady, D. D., eds. *Charge and Field Effects in Biosystems – 3*. Boston: Birkhauser. pp. 263–272.
- Smith, S. D., McLeod, B. R., Liboff A. R., Cooksey, K. E. (1987). Calcium cyclotron resonance and diatom motility. *Bioelectromagnetics* 8:215–227.
- Stevens, R. G. (2006). Circadian disruption and breast cancer: from melatonin to clock genes. *Epidemiology* 16:254–258.
- Thomas, J. R., Schrot, J., Liboff, A. R. (1986). Low-intensity magnetic fields alter operant behavior in rats. *Bioelectromagnetics* 7:349–357.
- Vincze, G., Szasz, A., Liboff, A. R. (2008). New theoretical treatment of ion resonance phenomena. *Bioelectromagnetics* 29:380–386.
- Vorobyov, V. V., Sosunov, E. A., Kukushkin, N. I., Lednev, V. V. (1998). Weak combined magnetic field affects basic and morphine-induced rat's induced EEG. *Brain Res.* 781:182–187.
- Webb, H. M., Brown Jr, F. A. (1965). Interaction of diurnal and tidal rhythms of activity in the fiddler crab, *Uca Pugnax*. *Biol. Bull.* 129: 582–591.
- Wiltshko, W., Wiltshko, R. (1972). Magnetic compass of European robins. *Science* 176:62–64.
- Zhadin, M. N., Deryugina, O. N., Pisachenko, T. M. (1999). Influence of combined DC and AC magnetic fields on rat behavior. *Bioelectromagnetics* 20:378–386.
- Zhadin, M. N., Novikov, V. V., Barnes, F. S., Pergola, N. F. (1998). Combined action of static and alternating magnetic fields on ionic current in aqueous glutamic acid solution. *Bioelectromagnetics* 19: 41–45.